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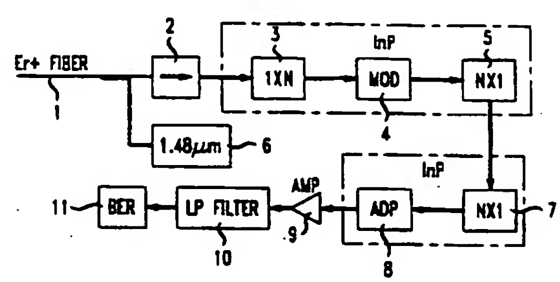
(54) Spectrum-sliced fiber amplifier light source for multi-channel wavelenght-division-multiplexed applications.

(57) The present invention relates to a potentially inexpensive light source for multi-channel wavelength-division-multiplexed (WDM) applications. The high-power amplified spontaneous emission (ASE) from a fiber amplifier, which is already in the optical fiber, is efficiently divided into many channels using a WDM demultiplexer. This "spectrum-sliced" ASE is used as light sources for WDM systems rather than several wavelength-selected DFB lasers.

FIG. 1



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Field of the Invention

The present invention relates to a cost efficient spectrum-sliced fiber amplifier light source to be used with practical wavelength-division-multiplexed (WDM) systems for both long-distance (~100 km) and local loop applications.

Information Disclosure Statement

Recent achievements in optical amplifiers revitalize the practicality of wavelength-division-multiplexed (WDM) systems for both long-distance transmission and local-loop applications. However, WDM systems are envisioned to have a multiple number of transmitter lasers operating at different wavelengths. Thus, these transmitter lasers should be wavelength-selected for each channel and controlled to operate at a specific wavelength to the end of a system's lifetime. However, this process would increase cost and complexity.

There have been a few attempts to overcome this problem by using broadband light sources. For example, the broadband light from 1.3-μm light emitting diodes (LEDs) or superluminescent diodes (SLDs) was "spectrum-sliced" using grating-based demultiplexers and used in WDM systems. Thus, there was no need for wavelength-selecting transmitter lasers and identical LEDs were used for every channel. However, the transmission rates were limited to 2 Mb/s - 150 Mb/s over the distances less than 7 km due to the insufficient power inherent in LEDs. Recently, the transmission distance has been extended to 110 km at 140 Mb/s using 1.5-μm SLDs and an erbium-doped fiber amplifier (EDFA).

M.H. Reeve, A.R. Hunwicks, W. Zhao, S.G. Methley, L. Bichers and S. Hornung, "Led Spectral Slicing For Single-Mode Local Loop Applications", Electronics Letters, Vol. 24, No. 7 (March 31, 1988), pp. 389-390, and S.S. Wagner and T.E. Chapuran, "Broadband High-Density WDM Transmission Using Superluminescent Diodes", Electronics Letters, Vol. 26, No. 11 (May 24, 1990), pp. 696-697, describe "spectrum-sliced" light emitting diodes (LEDs) and superluminescent diodes (SLDs) using grating-based demultiplexers. Further, an article, P.D.D. Kilkelly, P.J. Chidgey, and G. Hill, "Experimental Demonstration of a Three Channel WDM System Over 110 km Using Superluminescent Diodes", Electronics Letters, Vol. 26, No. 20 (September 27, 1990), pp. 1671-1673, addressing transmission distance using SLDs and an erbium-doped fiber amplifier (EDFA) has been written.

However, none of these articles considers a spectrum-sliced fiber amplifier light source for multichannel WDM applications encompassed by the present invention.

Summary of The Invention

The present invention pertains to the use of broadband light as an inexpensive multi-channel wavelength-division-multiplexed (WDM) light source, based on the following:

(1) obtaining strong amplified spontaneous emission (ASE) in excess of 40 mW from an erbium-doped fiber amplifier (EDFA), and

(2) utilizing integrated optic WDM multiplexers for efficient optical multiplexing.

Brief Description of The Drawings

Figure 1 shows a schematic diagram of the proposed multi-channel WDM light source. MOD is an array of N modulators. An identical wavelength-sensitive 1xN demultiplexer could be used at the receiver end;

Figure 2 shows an experimental set-up. BP is an optical bandpass filter (bandwidth; 1.3 nm). P and PC are a polarizer and a polarization controller, respectively;

Figure 3 shows the ASE spectrum of an EDFA with and without the bandpass filter. The backward ASE power was about 21 mW at the pump power of 40 mW. The ASE power within the filter bandwidth (1.3 nm) was about 0.9 mW; and,

Figure 4 shows the measured bit error curves at 622 Mb/s, 1 Gb/s, and 1.7 Gb/s: (□) a 1.5-μm DFB laser; (●) the spectrum-sliced ASE light source (bandwidth; 1.3 nm); (o) the spectrum-sliced ASE light source (bandwidth; 0.6 nm).

Detailed Description of The Invention

Figure 1 shows the schematic diagram of the proposed WDM light source. The EDFA 1 provides much more powerful ASE light 2 into the single-mode fiber than semiconductor devices (e.g. LEDs, SLDs, or amplifiers). The ASE light 2 is efficiently split into many WDM channels using a wavelength-sensitive 1xN WDM demultiplexer 3, modulated individually, and multiplexed back into a single-mode fiber using a wavelength-sensitive Nx1 WDM multiplexer 5. The (de)multiplexers and modulators 4 could be fabricated monolithically on Inp substrates. Figure 1 also shows a system for receiving the spectrum-sliced light source including a wavelength-sensitive Nx1 WDM demultiplexer 7 and an APD 8, biased at 60v, for attenuating and detecting the modulated signal. The detected signal is further amplified 9 and filtered with a lowpass filter 10, and then sent to an error detector 11 for the BER measurement. Thus, this simple arrangement with an EDFA (requiring only one pump laser 6) can provide an economical light source for a multiple nimber of WDM channels.

The detection of ASE light generates spontane-

ous-spontaneous beat noise, which consists of a dc part arising from the beat between the same optical frequency components and an ac part due to the beat between the different frequency components. Thus, when the ASE is used as a WDM light source, we may consider the dc ASE power, I^2_{ASE}, as carrier and the time-varying ac part, I^2_{sp-sp}, as noise. These terms are given by

$$I^2_{ASE} = \{e \eta m n_{sp} (G - 1)B_o\}^2 \quad (1)$$

$$I^2_{sp-sp} = \frac{2 I^2_{ASE} B_e}{m B_o} \quad (2)$$

where, η is the detection quantum efficiency, m is the number of polarization modes, n_{sp} is the spontaneous emission factor, G is the amplifier gain, B_o is the optical bandwidth, and B_e is the electrical bandwidth of the receiving sysytem. Thus, the signal-to-noise ratio (SNR) of ASE light at the receiver is given by

$$SNR = \frac{I^2_{ASE}}{I^2_{sp-sp} + I^2_{shot} + I^2_{ckt}} \quad (3)$$

where, I^2_{shot} and I^2_{ckt} are the noise power produced by the ASE shot noise and the receiver electronics, respectively. Neglecting the electrical noise, it becomes

$$SNR = \frac{m B_o}{2 B_e} = \frac{B_o}{B_e} \quad (4)$$

since m = 2 for EDFAs. In traditional LED transmission systems, the spontaneous-spontaneous beat noise is negligible because of the large optical bandwidth. However, it becomes dominant over electrical noise and limits the total transmission capacity, T, when the optical bandwidth per channel is significantly reduced as in the proposed WDM light source. Since the electrical noise is neglected, there is no noise when the ASE light is not present (i.e. for space). Thus, the Q-parameter at the receiver is given by $Q \approx I_{ASE}/\sqrt{I^2_{sp-sp}} = \sqrt{SNR}$. For the Gaussian noise approximation, Q = 7.65 when the bit-error-rate (BER) is 10^{-14}. Thus, the corresponding SNR is about 60. The B_e is assumed to be 0.7 times the transmission rate, B. Then, T is given by

$$T = NB \approx \frac{B_a}{42 M} \quad (5)$$

where, $N(=B_a/MB_o)$ is the number of channels, B_a is the bandwidth of an EDFA (~40nm), and M is the multiplication factor given by the channel spacing divided by B_o. Thus, T is not dependent on the transmission rate of each channel, B. The ultimate value of T would be about 120 Gb/s if the channel spacing is allowed to be as narrow as B_o(M=1). However, the realistic estimation of T would be about 40 Gb/s since the channel spacing should be at least 3 times the B_o(M=3) to avoid crosstalk.

The experimental set up is shown in Figure 2. A 150-m long erbium-doped fiber 11 was pumped in counter-propagating direction with a 1.48-μm laser 66. The backward ASE power was measured to be about 21 mW at a pump power of 40 mW. An optical isolator (~30 dB) was placed at the output of an erbium-doped fiber to suppress lasing. An optical bandpass filter 22 was used to simulate the WDM demultiplexer. The bandpass filter was centered at 1.56 μm and had a 3-dB bandwidth of 1.3 nm. The ASE power within this bandwidth was about 0.9 mW. Figure 3 shows the ASE spectrum with 310 and without 320 the bandpass filter.

An optical polarizer 33 and a polarization controller 44 were used at the input of the polarization-sensitive $LiNbO_3$ modulator 55, resulting in a 3 dB loss of both the optical ASE power and the SNR (since the number of polarization mode becomes m=1). However, these losses would be recovered if the $LiNbO_3$ modulator was replaced with a polarization-insensitive electroabsorption modulator. The ASE light was modulated at 622 Mb/s, 1 Gb/s, and 1.7 Gb/s with a 2^{15}-1 bit pseudorandom sequence. The modulated signal was attenuated and detected using an InGaAs APD 77. The APD was biased at 60 V. The detected signal was then amplified 88 and filtered with a lowpass filter 99, and sent to an error detector 111 for the BER measurement. The bandwidth of the lowpass filter was set to be about 0.7 times the bit rate, yielding 400 MHz, 700 MHz, and 1.3 GHz.

We compared the receiver sensitivity of a system using the spectrum-sliced ASE light and a conventional 1.5-μm DFB laser. The laser wavelength (1.548 μm) was close to the center-wavelength of the ASE light (1.560 μm). Figure 4 shows the measured BER curves. A 400-MHz lowpass filter was used for 622-Mb/s data. Thus, the SNR of the spectrum-sliced ASE light (bandwidth; 1.3 nm) with single polarization (m=1) was estimated to be about 23 dB from equation (4). At 622 Mb/s, the receiver sensitivity was almost identical using the ASE light source 41 and the DFB laser 42. For 1-Gb/s data, the electrical bandwidth was increased to 700 MHz, thus the SNR was degraded to about 20.6 dB. The power penalty was measured to be about 0.6 dB at an error rate of 10^{-9}. The SNR was degraded further to about 17.9 dB for 1.7-Gb/s data due to the increased electrical bandwidth of 1.3 GHz. The power penalty was about 1.6 dB.

We also reduced the optical bandwidth of ASE light to 0.6 nm 43. The SNR was then degraded to about 19.7 dB when a 400-MHz lowpass filter was used for 622-Mb/s data. The resulting power penalty was about 0.5 dB. When this ASE light was used for 1-Gb/s data, the SNR was 17.3 dB and the power penalty was about 1.4 dB. However, for 1.7-Gb/s data, the SNR was degraded to 14.6 dB and an error floor was observed at about 5×10^{-9}. This is in a good agreement with the theoretically calculated SNR of 15.2 dB for the above error rate. These experimental results confirm the calculated SNR of about 18 dB

needed for the error-free transmission (BER=10^{-14}). Thus, even the 0.6-nm ASE light could be used for 1.7-Gb/s data if both polarization modes are used (m=2). Assuming that the channel spacing is about 3 times B_o, we should be able to place twenty-two 0.6-nm channels within the bandwidth of an EDFA. Then, the total transmission capacity, T, is about 37 Gb/s, which is in a good agreement with the estimated capacity of 40 Gb/s from equation (5).

In summary, we propose a potentially inexpensive light source based on an EDFA and an integrated optic WDM demultiplexer for multi-channel WDM applications. The SNR of such incoherent light source depends on the ratio of the optical and electrical bandwidth due to the spontaneous-spontaneous beat noise. Thus, it is necessary to increase the optical bandwidth and/or decrease the electrical bandwidth to improve the SNR, which, in turn, determines the total capacity of a WDM system using such light sources. To demonstrate the principle, we filtered the ASE light with an optical bandpass filter (bandwidth; 1.3 nm) and used for the transmission of 622 Mb/s, 1 Gb/s, and 1.7 Gb/s data. The penalty in the receiver sensitivity was negligible at 622 Mb/s and increased with the bit rates. This is because the SNR of the spectrum-sliced 1.3-nm ASE light degraded as wider electrical bandwidth is needed for the system operating at a higher bit rate. The penalty also increased when the optical bandwidth was reduced. These experimental results indicate that the ASE light should have the SNR better than about 18 dB for the error-free transmission (BER < 10^{-14}), as expected from the simple Gaussian noise approximation. From this requirement, we estimate that the realistic capacity of a WDM system using this light source would be about 40 Gb/s, assuming the channel spacing should be at least 3 times the optical bandwidth of each channel. The chromatic dispersion would be a lesser problem for these light sources than conventional broadband sources such as LEDs due to their relatively narrow optical bandwidth. Thus, we believe that these light sources could help the realization of practical WDM systems for both long-distance transmission (~100 km) and local loop applications.

Claims

1. A system for producing a light source for use with a multi-channel wavelength-division-multiplexed (WDM) system comprising:
   (a) a fiber amplifier (1) providing amplified spontaneous emission (ASE) light;
   (b) a laser (6) for pumping said fiber amplifier; and,
   (c) a WDM demultiplexer (3) for receiving and splitting said ASE light said demultiplexer being connected to a modulator (4), said modulator being connected to a WDM multiplexer (5) for combining the ASE light back into an optical fiber, thereby producing a spectrum-sliced light source for a multiple number of WDM channels.

2. The system of claim 1, wherein the WDM demultiplexer is a wavelength-sensitive 1×N demultiplexer.

3. The system of claim 1 or claim 2, wherein the ASE light, spectrum-sliced for each of said multiple number of channels, has an optical bandwidth, a detected dc part and a detected ac part, the dc part, I^2_{ASE}, given by:
$$I^2_{ASE} = \{e\eta m n_{sp}(G-1)B_0\}^2,$$
where, η is the detection quantum efficiency, m is the number of polarization modes, n_{sp} is the spontaneous emission factor, G is the amplifier gain, B_0 is the optical bandwidth of the spectrum-sliced ASE light and B_e is an electrical bandwidth of a receiving system;
and
the time-varying ac part, I^2_{sp-sp}, is given by:
$$I^2_{sp-sp} = \frac{2I^2_{ASE}B_e}{mB_0}$$

4. The system of claim 3, wherein the ASE light further comprises a signal-to-noise ratio (SNR) given by:
$$SNR = \frac{I^2_{ASE}}{I^2_{sp-sp} + I^2_{shot} + I^2_{ckt}}$$
where, I^2_{shot} and I^2_{ckt} are the noise power produced by ASE shot noise and the receiving system, respectively.

5. The system of claim 3 or claim 4, further comprising a channel spacing
$$\left(\frac{B_a}{N}\right),$$
said channel spacing being greater than the optical bandwidth (B_0) of the ASE light, with B_a being a predetermined bandwidth of said fiber amplifier and N being a predetermined number of channels.

6. The system of claim 5, further comprising a transmission capacity, T, of the receiving system given by:
$$T = \frac{B_a}{42M}$$
where M is a multiplication factor given by the

channel spacing

$$\left[\frac{B_a}{N}\right]$$

divided by the optical bandwidth (B_0).

7. The system of claim 6, wherein the value of B_a for said EDFA is approximately 40 nm.

8. The system of claim 6, wherein the transmission capacity is approximately 120 Gb/s.

9. The system of any of the preceding claims, wherein the fiver amplifier is an erbium fiber amplifier (EDFA).

10. A system for producing error free transmission for both long-distance transmission and local-loop applications including:
   I. a spectrum-sliced fiber amplifier light source comprising:
      (a) a fiber amplifier providing ASE light, said ASE light having an optical bandwidth;
      (b) a laser for pumping said fiber amplifier; and,
      (c) a WDM demultiplexer for receiving and splitting said ASE light, said demultiplexer being connected to a modulator, said modulator being connected to a WDM multiplexer for combining the ASE light back into an optical fiber, thereby producing a spectrum-sliced light source for a multiple number of WDM channels; and,
   II. a multi-channel WDM system for receiving said spectrum-sliced light source for producing substantially error-free transmission for both long-distance transmission and local-loop applications.

11. The system of claim 10, wherein the ASE light has a signal-to-noise ratio (SNR) given by:

$$SNR = \frac{B_0}{B_e}$$

with B_e being an electrical bandwidth of a receiving system.

FIG. 1

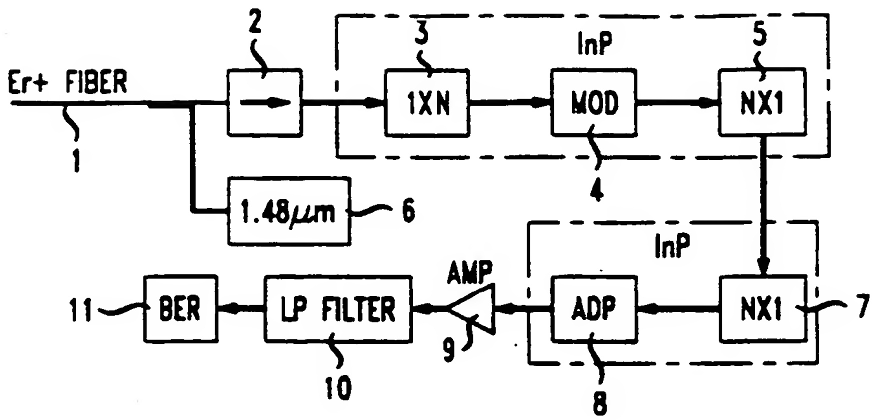

Er+ FIBER
1
2
3
InP
5
1XN
MOD
NX1
4
1.48μm
6
InP
AMP
11
BER
LP FILTER
ADP
NX1
7
9
10
8

FIG. 2

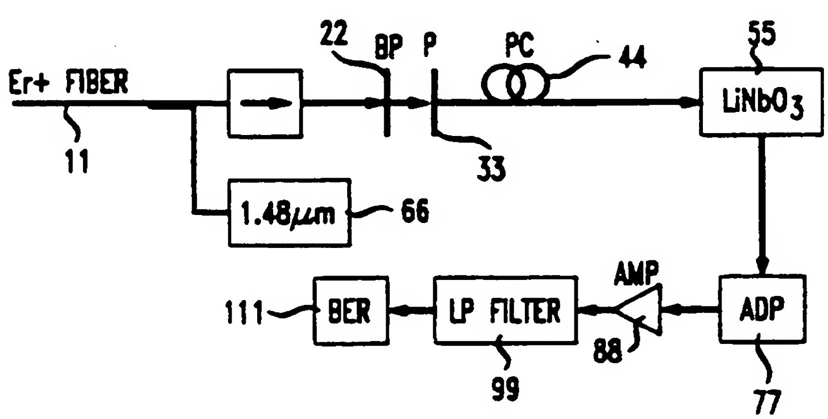

22
BP
P
PC
44
55
Er+ FIBER
LiNbO3
11
33
1.48μm
66
AMP
111
BER
LP FILTER
ADP
88
99
77

FIG. 3

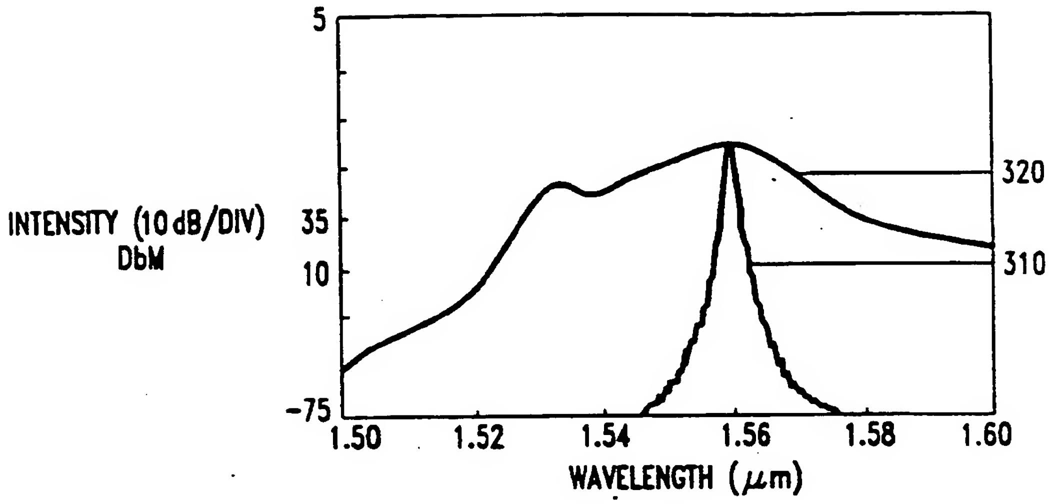
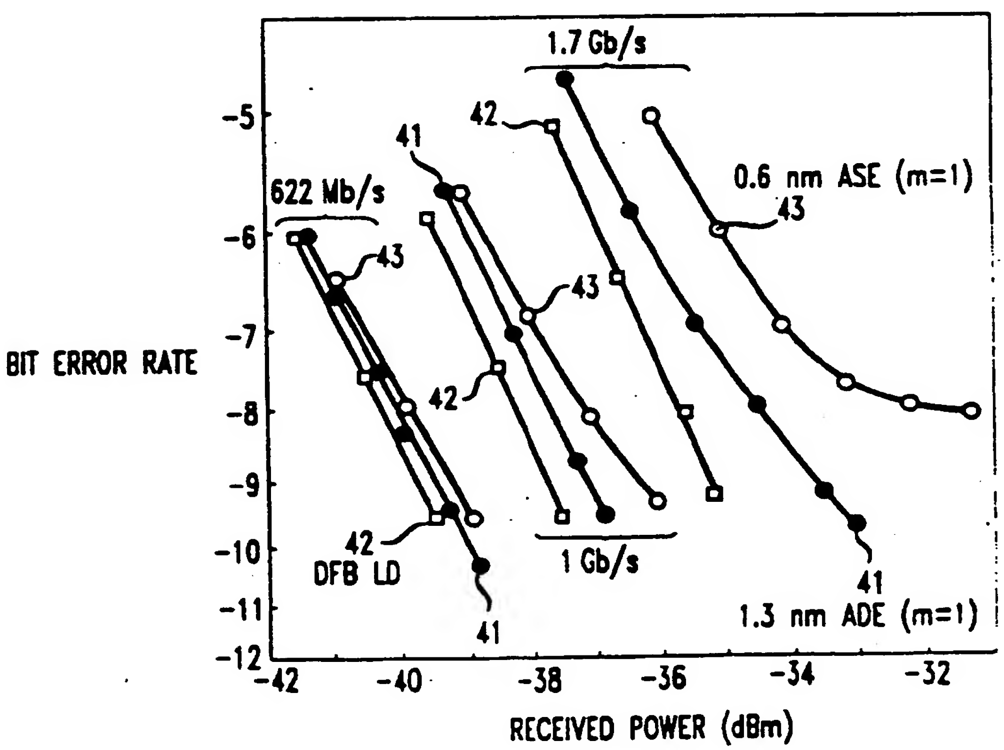

5
INTENSITY (10 dB/DIV)
DbM
35
10
-75
1.50
1.52
1.54
1.56
1.58
1.60
WAVELENGTH (μm)
320
310

FIG. 4


1.7 Gb/s
622 Mb/s
41
42
43
0.6 nm ASE (m=1)
BIT ERROR RATE
-5
-6
-7
-8
-9
-10
-11
-12
-42
-40
-38
-36
-34
-32
RECEIVED POWER (dBm)
DFB LD
1 Gb/s
1.3 nm ADE (m=1)

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 94 30 6931

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
X	JAPANESE JOURNAL OF APPLIED PHYSICS, vol.30, no.7BP2, 15 July 1991, TOKYO JP pages L1282 - L1284, XP000237725 Y.OHISHI ET AL. 'Pr3+ - doped superfluorescent fluoride fiber laser' * page L1282, paragraph 1 *	1,2,10	H01S3/06 H04B10/17
D,A	ELECTRONICS LETTERS., vol.26, no.20, 27 September 1990, ENAGE GB pages 1671 - 1673 P.D.D.KILKELLY ET AL. 'Experimental demonstration of a three channel WDM system over 110km using superluminescent diodes' * figure 1 *	1	
D,A	ELECTRONICS LETTERS., vol.24, no.7, 31 March 1988, ENAGE GB pages 389 - 390 M.H.REEVE ET AL. 'LED spectral slicing for single mode local loop application' * figure 1 *	1	TECHNICAL FIELDS SEARCHED (Int.Cl.6)
A	ELECTRONICS LETTERS., vol.27, no.3, 31 January 1991, ENAGE GB pages 261 - 263, XP000122387 H.FEVRIER ET AL. 'High-power, compact 1.48 um diode-pumped broadband superfluorescent fibre source at 1.55 um' * figure 1 *	1,9	H01S H04B
A	JOURNAL OF LIGHTWAVE TECHNOLOGY, vol.9, no.2, February 1991, NEW YORK US pages 147 - 154, XP000232637 C.R.GILES ET AL. 'Propagation of signal and noise in concatenated Erbium-doped fiber optical amplifiers'		

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	20 January 1995	Galanti, M

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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EUROPEAN SEARCH REPORT

Application Number
EP 94 30 6931

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	ELECTRONICS LETTERS., vol.28, no.13, 18 June 1992, ENAGE GB pages 1212 - 1213, XP000301390 M.ZIRNGIBL ET AL. 'Efficient 1x16 optical power splitter based on InP' ---		
P,X	IEEE PHOTONICS TECHNOLOGY LETTERS, vol.5, no.12, December 1993, NEW YORK US pages 1458 - 1461, XP000432998 J.S.LEE ET AL. 'Spectrum-sliced fiber amplifier light source for multichannel WDM applications' * the whole document * -----	1-11	

TECHNICAL FIELDS SEARCHED (Int.Cl.6)

The present search report has been drawn up for all claims

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THE HAGUE	20 January 1995	Galanti, M

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